(1)

UNMANNED GROUND VEHICLE
MASTER PLAN

July 1992

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GLOSSARY

ADM	advanced development model
AI	artificial intelligence
APG	Aberdeen Proving Ground
ARL	Army Research Laboratory
ASD	advanced system development
ATR/ATC	automatic target recognition/automatic target cueing
CARD	computer-aided remote driving
CCF	central control facility
CECOM	Communications and Electronics Command
COEE	concept of employment evaluation
C3	command, control, and communications
DARPA	Defense Advanced Research Projects Agency
DEMVAL	demonstration and validation
DoD	Department of Defense
DoE	Department of Energy
DT&E	development, test and evaluation
EMD	engineering and manufacturing development
EOD	Explosive Ordnance Disposal
EUT&E	early user test and evaluation
FELICS	Feedback-Limited Control System
FLIR	forward looking infrared
FO	fiber optic
FOV	field of view
FY	fiscal year
gHz	gigahertz
GPS	Global Positioning System
HMMWV	high mobility multi-purpose wheeled vehicle
hp	horsepower
INS	inertial navigation system
IOT&E	Initial Operational Test and Evaluation
IR	infrared
IUA	image understanding architecture
JPL	Jet Propulsion Laboratory
JPO	Joint Project Office

Kbps	kilobits per second
km	kilometer
LOS	line of sight
MBU	mobile base unit
MDARS-E	Mobile Detection Assessment Response System-Exterior
MMW	millimeter wave
MOA	memorandum of agreement
mph	miles per hour
mrad	milliradian
MW	microwave
NBC	nuclear, biological, and chemical
NDI	non-developmental item
NIST	National Institute of Standards and Technology
NLOS	non-line of sight
OCU	operator control unit
ORD	Operational Requirements Document
ORNL	Oak Ridge National Laboratory
OSD	Office of the Secretary of Defense
OT&E	operational test and evaluation
OUSD(A)/TS	Office of the Undersecretary of Defense (Acquisition)/ Tactical Systems
PE	program element
PIP	product improvement program
PSEMO	Physical Security Equipment Management Office
PSSE	physical security surveillance and enforcement
R&D	research and development
RCS	real-time control system
RDT&E	research, development, test, and evaluation
RECORM	Remote Control Reconnaissance Monitor
RF	radio frequency
RONS	Remote Ordnance Neutralization System
RRR	Rapid Runway Repair
RSTA	reconnaissance, surveillance, and target acquisition
RWG	robotics working group
S&T	science and technology
SINCGARS	Single Channel, Ground/Air Radio System
SSV	Surrogate Semiautonomous Vehicle
STV	surrogate teleoperated vehicle
TACOM	Tank and Automotive Command
T&E	test and evaluation
TUGV	Tactical Unmanned Ground Vehicle
TWP	Tactical Warfare Programs

UAV	unmanned air vehicle
UGV	unmanned ground vehicle
UGVCT	unmanned ground vehicle control testbed
UGVMP	Unmanned Ground Vehicle Master Plan
UGVTEE	UGV Technology Enhancement and Exploitation
VME	Versabus Module European
3-D	three dimensional

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I. SUMMARY

A. BACKGROUND

In FY 1990, in response to a Congressional request,[1] all Department of Defense (DoD) advanced development projects related to ground vehicle robotics were consolidated in a single program element under Office of the Secretary of Defense (OSD) direction (PE0603709D). Since then, OUSD(A)/TS, the Tactical Systems office [formerly the Tactical Warfare Programs (TWP) office] of the Office of the Undersecretary of Defense (Acquisition) [OUSD(A)], has been responsible for this program element (PE), providing policy and program direction, allocating appropriated funds to projects within this PE, and carefully monitoring the progress of these projects. The Services and the Defense Advanced Research Projects Agency (DARPA) are responsible for the conduct and daily management of the projects.

As part of this consolidation, existing and emerging requirements were analyzed and overall rationale and investment strategy for the robotics program were developed. The various projects underway or proposed by the Services were reviewed. Several were terminated and those that were selected were restructured to produce a more focused and cost-effective robotics program. The results of this process were reported in the 1990 Unmanned Ground Vehicle Master Plan (UGVMP).[2]

In last year's UGVMP,[3] the individual projects were crystalized, interrelated, and more strongly tied to the DoD acquisition process, shown in Figure 1. In addition, a robotics technology maturation thrust was initiated to establish a national research and development (R&D) base for second-generation UGVs. The OSD PE encompasses advanced technology development at the component level and advanced development of system prototypes (Figure 1).

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1 Report 101-132 from the Senate Committee on Appropriations on the Department of Defense Appropriations Bill, 1990.

2 Unmanned Ground Vehicle Master Plan, Department of Defense, April 1990.
Here and hereafter, the term unmanned ground vehicle (UGV) is used in a general sense to include a range of applications. The term Tactical Unmanned Ground Vehicle (TUGV) will refer to a specific project, described below, which is developing one class of UGVs.

3 Unmanned Ground Vehicle Master Plan, Department of Defense, July 1991.

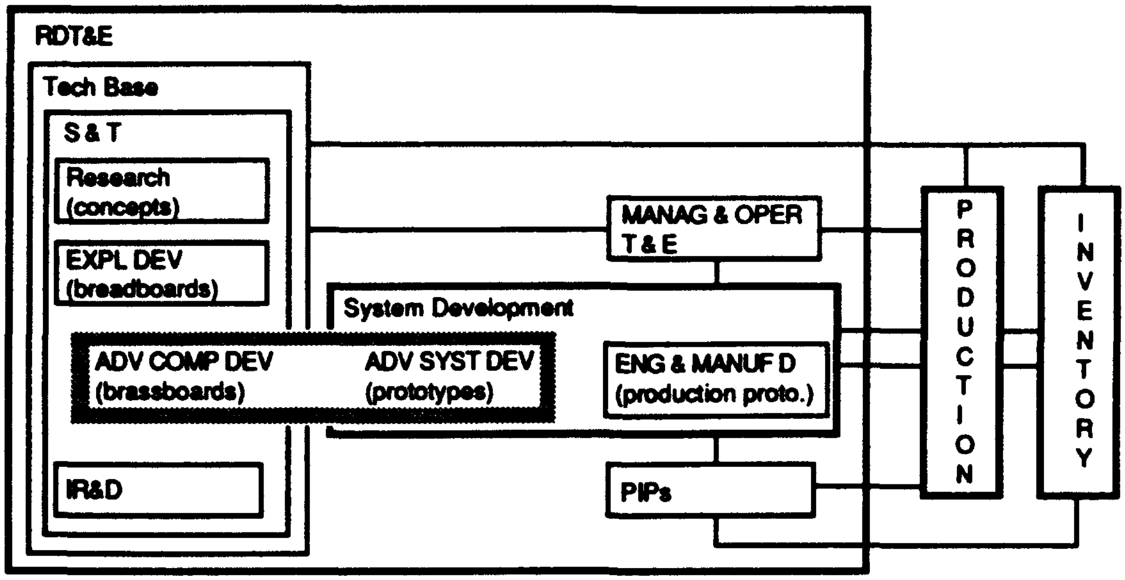

Figure 1. Robotics Program Focus (PE0603709D)

This year's UGVMP contains an update, expansion, and adjustment of last year's UGVMP. It also discusses potential future UGV developments.

B. PURPOSE AND SCOPE

The purpose of the UGVMP is to provide a single, integrated DoD document that lays out the strategy for introducing supervised robotic vehicles into our forces and the plan for development and acquisition of UGV systems. The UGVMP describes the conceptual and management framework within which robotics projects are being pursued, the details of these projects, and the relationships among them. OSD is using the UGVMP as a management tool in fulfilling its responsibilities for overseeing the robotics program.

The program has been structured to progress from teleoperation--where a remotely located human directly controls the UGV--to reliance on autonomous onboard performance of UGV functions with the operator in a supervisory role and able to supervise multiple UGVs concurrently.

In contrast to man-operated materiel, the component development of automation technology for UGVs must be done as an integral part of the total system. The robotics program builds on the research and exploratory development carried out by the Services and Defense Agencies, integrating demonstrated component technologies into prototype systems that promise high operational payoffs. Advanced system development will result in prototypes that, from an engineering aspect, are ready for a Milestone II decision.

The current UGV investment focuses on:

- Near- and mid-term advanced system development projects that have Service support
- Overcoming technological barriers that impede the development of highly autonomous UGVs.

Although unmanned air vehicles (UAVs) are not included within the plan, UGV/UAV interoperability of remote command and control stations and commonality of architectures are being pursued. Technologies, such as artificial intelligence, that other programs are developing are being used for UGV systems. Conversely, plannin; is underway to apply the technology base projects within the UGV program to other programs such as the physical security program.

C. BASIS FOR UGV SYSTEMS PLANNING

The potential payoffs of UGVs include the following:

- Reduced risk to human life and increased operational flexibility in combat or other hazardous environments
- Economy of manpower or reduced costs in operations done repetitively (e.g., logistics) where manpower savings more than offset investments in equipment
- Reduced training costs and increased training realism
- Improved performance where automated systems either perform better than humans or eliminate the system compromises required by human physiological limits (comfort, fear, fatigue, vibration, etc.)
- Force multiplication where operators with UGVs bring substantially more capability to bear than would be possible by individual troops without UGVs.

There are strong reasons for believing that the structure and operations of future land forces will depend heavily on robotic systems:

- There are a variety of potential applications of robotics to land operations that can increase efficiency and safety. These include reconnaissance and surveillance, target engagement, logistics, runway repair, minefield detection and neutralization, explosive ordnance disposal, physical security, and operations in contaminated environments. (The threat of encountering chemical and biological weapons in Third World conflicts is growing rapidly.)
- Force size will be substantially smaller (e.g., forward-deployed forces in Europe) but without corresponding reductions in areas of responsibility.
- The hardware that is necessary for many of these applications is developing rapidly. Modern sensors, computers, and communication links can acquire,

process, and transmit data far beyond the capabilities of individuals restricted to manual operations.

- Robots and robot-like devices continue to grow in commercial importance with applications that range from cruise control of automobiles to complex autopilots and from manufacturing to medicine.

In a number of ways, lessons learned from the recent conflict in Southwest Asia reenforce the view that automation and robotic systems will play a major role in realizing the force multiplication required to offset continuing reductions in land forces:

- For the first time, UAVs were widely used in combat.
- Land forces confronted the immediate threat of chemical weapons.
- A hurried request for remotely operated, mine-clearing tanks, and shallow water craft was made.
- High technology weapons demonstrated the effectiveness of autonomous guidance.
- Desert Storm set a standard of minimal friendly casualties against which the results of future conflicts will be measured.

Although the potential applications and payoffs of UGV systems are apparent and although today's sensors and computers, coupled interactively with humans, can meet the requirements for many of these applications, for many other applications the software that is required to approximate human capability to integrate data and exercise control authority does not exist. Developing such software for future autonomous systems is the major challenge. Teleoperation avoids the severe software challenges of autonomous operation but involves significant communications, man-machine interface, and human factors issues. Nevertheless, teleoperation is feasible today; except for a few highly structured applications, autonomous operation is not.

Given the status of robotics technology and user requirements, current DoD planning for UGV systems stresses two types of system development. The first type involves UGVs that must operate on the battlefield with other land combat systems and forces. The TUGV development is the near-term thrust of the UGV program in this category. The second type involves relatively narrow, but cost-effective, applications other than land combat that have limited and achievable requirements for automating human control functions. These narrower projects develop specific robotics techniques and also support the goal of gaining user acceptance of robotic systems.

The UGV program strategy is based on a coordinated evolution of demonstrated capabilities and user requirements. In the near term, teleoperation and teleassistance are

emphasized, together with extensive user opportunities to gain experience with prototypes. In the mid-term, supervised robotics will be demonstrated and introduced for navigation and/or reconnaissance, surveillance, and target acquisition (RSTA) functions. In the far term, highly robotic systems based on artificial intelligence (AI) will be developed not only for autonomous TUGVs but also as upgrade options for manned systems. Far-term robotics research is being conducted mainly by DARPA.

The UGV plan described in this report has been structured to maximize future use across the Services, to focus limited resources on existing and emerging requirements, and to preclude duplicative activities. Technology programs have been focused on the system applications that were selected. Specific programmatic plans, described below, have been developed to ensure that appropriate technology is demonstrated and that demonstrated technology is integrated into system development.

Considerable attention has been given to fostering organizational relationships (among DoD components and between them and other agencies, universities, and industry) that will assure technology transfer and maximize the productivity of the funds expended under the Joint Robotics Program. These relationships include:

- Development of the TUGV under a memorandum of agreement (MOA) between the Army and Marine Corps
- Collaboration among the advanced system development and technology projects for demonstration and integration of technology prior to engineering and manufacturing development (EMD)
- Development of robotic UGV navigation technology under an MOA between DARPA and OUSD(A)/TS that incorporates technology transfer from academia to industry and Government
- Pursuit of joint DoD and Department of Energy (DoE) development opportunities
- Colocation of the UAV-Short Range, UAV-Close Range, and UGV project offices to facilitate cooperation in the development of employment concepts and common control architectures.

D. PROGRAM SUMMARY

Figure 2 shows the FY 1992 robotics program consisting of three advanced system developments and two technology enhancement and maturation projects as well as one program that was funded in earlier years.

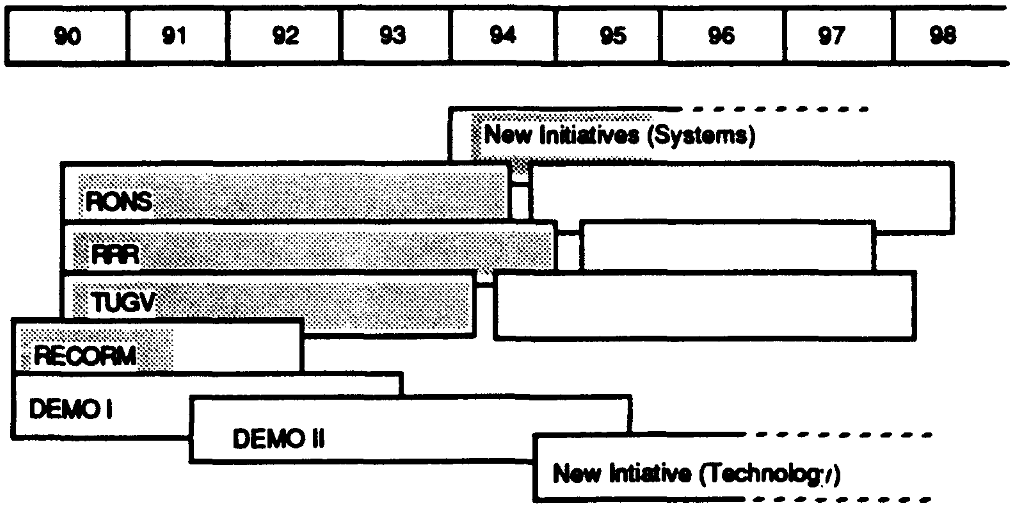

Figure 2. Robotics (UGV) Program

The Remote Control Reconnaissance Monitor (RECORM) is now in EMD and is funded through the joint Explosive Ordnance Disposal (EOD) program. This lightweight, two-man transportable UGV system will allow EOD personnel to visually search for, identify, and determine the condition of unexploded ordnance from a remote, safe location. The Milestone III decision is planned for October 1993. The current procurement plan calls for 340 vehicles with a unit price of about $110,000.

The Remote Ordnance Neutralization System (RONS), now in advanced system development (ASD), is also an EOD UGV acquisition project. Transition to EMD is planned for FY 1994 with production commencing in FY 1998. This project is developing a remotely operated mobile platform with closed-circuit TV, a six-degrees-of-freedom manipulator, and a suite of EOD-unique tools with automated tool exchange. This UGV system will provide EOD personnel safe separation from hazardous accident/incident sites where explosive, chemical, or radiation risks are present. The current plan calls for procurement of about 200 vehicles.

The Rapid Runway Repair (RRR) UGV is another advanced system development effort to remove personnel from high threat/hazardous environments. The RRR UGV, which will be capable of automated driving to a damaged runway site, finding and assessing the damage, and repairing it as required, supports the Air Force requirement for sustained operation of air fields following an enemy attack. The guided robotic positioning and operation of heavy equipment represents a unique set of requirements that bring effector technology for civil engineering into the overall robotics program. Potential civilian applications of this technology, especially for work in hazardous environments, are being explored with DoE. An EMD decision is planned for FY 1994 with procurement

commencing in FY 1997. The current estimate of procurement quantity is approximately 125 UGVs.

The TUGV is a joint Army and Marine Corps effort to develop UGVs for battlefield operations. This project was initiated by Congressional request in FY 1990. Its overall objective is to increase the effectiveness and survivability of combined arms forces by extending the control radius of the soldier on the battlefield. The near-term objective is to field by 1998 a teleoperated/teleassisted TUGV with the remotely located operator capable of performing RSTA functions; nuclear, biological, and chemical (NBC) detection; and laser designation. The near-term program includes extensive user familiarization with surrogate teleoperated vehicles (STVs) in order to assess operational benefits and liabilities and to assist in refining requirements before entering EMD in FY 1994. The current plan is to procure about 1,200 TUGVs.

The RRR project has less demanding requirements for navigation and communications than the TUGV. Because of the structured setting in which it will operate, RRR navigation can incorporate more robotic features.

These and future UGV acquisition projects are supported by a technology enhancement program designed to exploit and mature robotics-related technology advances that are critical for the UGV acquisition process. Its focus is on providing the technology and the mission capabilities required for the first generation TUGV, including product improvement, and for the relatively narrow applications of the other UGVs. The two projects--denoted by DEMO I and DEMO II--advance critical UGV component technologies and demonstrate system integration of these components. DEMO I and DEMO II are following a progression from manpower-intensive teleoperation through supervisory control to force-multiplying robotics levels of autonomy.

DEMO I will be essentially complete this year, having achieved its principle objective of maturing and demonstrating critical system component technologies for first-generation UGVs. The emphasis in DEMO I has been on reducing operator workload while enhancing performance of the RSTA mission of TUGVs. Based on the results of performance tests, selected technologies will be integrated onto the STV and carried through the TUGV advanced system development phase by the UGV JPO.

DEMO II started last year with the objective of developing, within the next 5 years, those navigation and other technologies that are necessary to move UGV capabilities from teleoperation to supervised robotics. This includes RSTA functions while the UGV is

moving, automated communication with other vehicles and with the supervising command and control network, and workload-partitioning among vehicles.

In order to respond to user requirements as they evolve, the longer-term goals of the robotics (UGV) program are as follows:

- The realization of mature technology for a supervised UGV by the year 2000
- The capability of fielding autonomous UGV systems by the year 2010.

Even though program resources preclude any new initiative before FY 1994, candidate technologies and applications are being examined. Potential future acquisition projects are discussed in Section II.F.

II. UGV PROGRAM STRATEGY AND MANAGEMENT

Chapter I described the broad rationale for the UGV program. This chapter continues the discussion of rationale by focusing on each of the major components of the program and the role of individual projects within those components. Management aspects of the program are highlighted.

A. OVERVIEW

As stated in Chapter I, the following three projects are in ASD and are being funded under PE0603709D:

- Tactical Unmanned Ground Vehicle (TUGV)
- Rapid Runway Repair (RRR)
- Remote Ordnance Neutralization System (RONS)

These (and future) projects are supported by UGV Technology Enhancement and Exploitation (UGVTEE) tasks that are addressing technologies critical to the timely development of UGV systems. Two extensive series of technology maturations and demonstrations are underway. These efforts are referred to as DEMO I and DEMO II and are discussed in Section E below. They directly support the various UGV functional needs, planned demonstrations, and future product improvements.

Table 1 shows the overall funding structure of the UGV program. Based on DoD budget guidance, the plan assumes a constant level of annual funding of approximately $21 million. The majority of this amount is planned for 6.3B development programs; a breakdown of this funding among TUGV, RRR, and RONS is shown in Table 2.

Table 2 displays the funding planned for TUGV, RRR, and RONS up to EMD. Coincidentally, EMD is scheduled to occur in FY 1994 for each of these programs. The Services are responsible for EMD funding. Candidate new initiatives for FY 1994 and FY 1995 are discussed in Section F. Next year's UGVMP will describe the FY 1994 plan in detail.

Table 1. Planned Funding for PE0603709D ($M)

	Prior Years	FY92	FY93	FY94	FY95[a]
Development Programs	21.25	11.80	10.90	8.50	9.50
Technology Base (UGVTEE)	19.78	8.00	8.00	9.00	9.00
Study, Taxes	.79	.73	.52	.32	.50
Total	41.82	20.23	19.42	17.82	19.00

[a] No FY 1995 funds have been committed at this time.

Table 2. Planned Funding for 6.3B Development Programs ($M)

	Prior Years	FY92	FY93	FY94	Total
TUGV	14.35	8.10	7.80	6.00	32.95
RFR[a]	2.75	2.00	1.50	1.00	8.80
RONS[b]	1.50	1.70	1.60	1.50	6.80

[a] In addition to the amounts shown, the Air Force has budgeted $0.25 million in FY 1990, $0.375 million in FY 1991, $0.325 million in FY 1992, and $0.30 million in FY 1993 and FY 1994.

[b] In addition to the amounts shown, the Navy has budgeted $0.40 million in FY 1992 and $0.90 million in FY 1993.

B. TACTICAL UNMANNED GROUND VEHICLE (TUGV)

In FY 1990, an MOA established the Joint Army/Marine Corps TUGV program with the Army as lead Service and the Marine Corps providing the project manager. The need for the TUGV arises from the convergence of two major trends. First, the lethality of the modern battlefield has increased dramatically. Proliferation of modern precision-guided munitions and chemical and biological weapons and developments in directed-energy weapons necessitate commensurate improvements in technology to extend the survivability of individual soldiers and marines. Second, reductions in force structure require materiel advances that are force multipliers. The overall purpose of the TUGV program is to increase the effectiveness and survivability of combined arms forces by extending the control radius of human presence on the battlefield. Remote operation is particularly important for the most forward deployed forces who are most at risk, including the risk of fratricide.

The long-term objective of the TUGV program is to extend the operational capability to perform RSTA-related missions and enhance soldier survivability, without introducing limitations that are not present in alternative manned systems. This can best be accomplished through increased automation in conjunction with innovative tactics. Future

TUGVs will allow an operator to control multiple vehicles and oversee several missions. DEMO II is developing this capability (see Section E.2 below). Other TUGV characteristics such as mobility, deployability, and endurance should match or exceed those of comparable manned systems.

1. System Description

The first generation TUGV will be a teleoperated, lightweight, mobile ground system for the infantry and Marine Corps that is navigated to an assigned position to provide remote reconnaissance and surveillance over prolonged time periods. This system will significantly lessen the exposure of combat soldiers and marines to hazardous and lethal environments. The initial requirement documents[1] specify TUGV capabilities that include RSTA with laser designation and weapon targeting; NBC detection and surveillance; obstacle detection and breaching; and the ability to employ standard infantry weapons for self-defense. The principal focus of the first generation TUGV is on the RSTA mission. By using highly modular subsystems, the TUGV can be readily upgraded when new technologies become available.

The initial system is envisioned to consist of an operator control unit (OCU), various mission modules, redundant data links, and a mobile base unit (MBU). The OCU is the command and control station from which both the MBU and its mission modules are remotely operated. The mission modules are specialized equipment packages (e.g., sensors, lasers, and processors for the RSTA mission). The TUGV will have redundant video data links between the MBU and the OCU. Current candidates include a fiber optic (FO) cable, narrow-band RF (with data compression), and wide-band (line-of-sight) RF. The first generation MBU will be based on an existing, non-developmental item (NDI) chassis. The two principal candidates are the high mobility multi-purpose wheeled vehicle (HMMWV) and a militarized all-terrain vehicle. However, the equipments mounted on the MBU, which include navigation equipment, onboard computers, and driving actuators, require varying amounts of development and integration. Next year's UGVMP will give a detailed description of the first generation TUGV after the final operational requirements are established.

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1 Army Operational and Organizational (O&O) Plan, November 1990, Marine Corps Initial Operational Requirement (ISOR), December 1990.

2. Technical Program Plan

Figure 3, an overview of the TUGV program, shows the parallel, interacting progression of system hardware and software development, tests, demonstrations, and supporting studies.

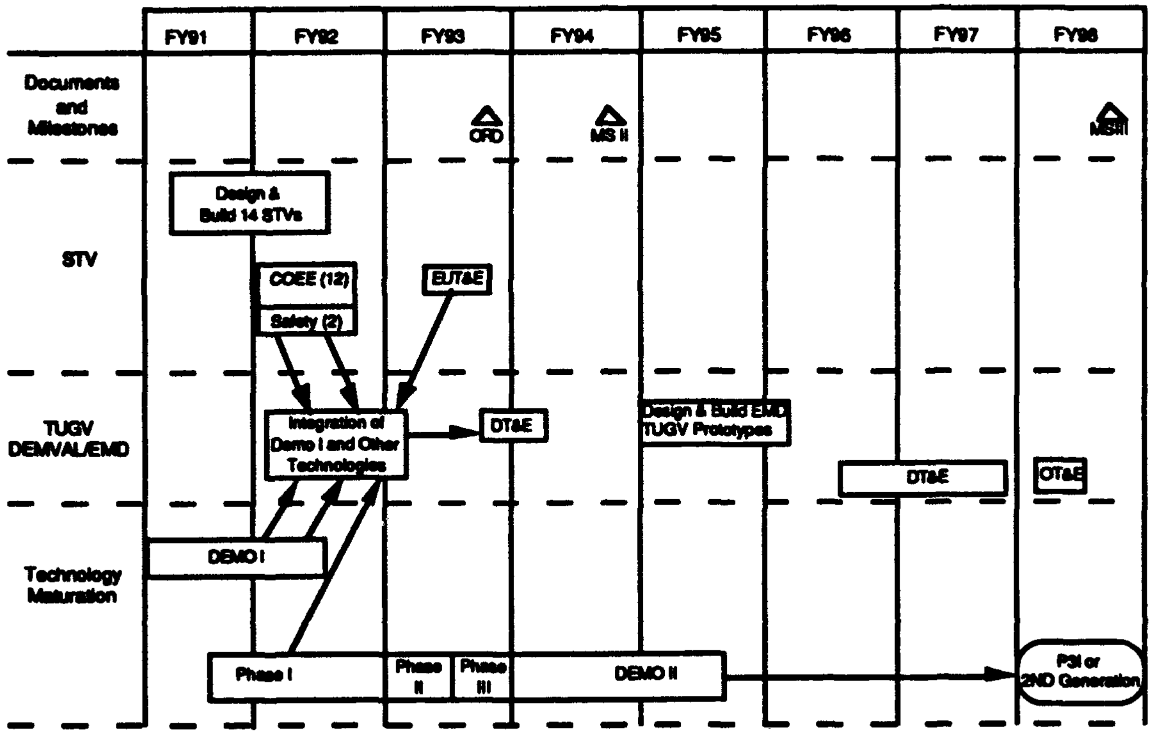

Figure 3. TUGV Program Plan and Schedule

Advanced system development of the TUGV has two parts.

1. Acquisition of NDI STVs, properly modified for teleoperated navigation and RSTA to
   - Establish the limitations and usefulness of NDI TUGVs
   - Formulate and evaluate concepts of employment
   - Engage the user in early test and evaluation for refining the operational requirements.

2. DEMVAL[2] risk reduction program to

- Evaluate and select teleassistance technologies provided by the DEMO I technology maturation program
- Integrate the selected technologies in the NDI vehicle
- Test integrated teleassistance technologies in terms of their ability to reduce operator workload and enhance performance.

A contract for 14 STVs was awarded in December 1990, and these have been delivered. The basic STV is a relatively small, lightweight, teleoperated UGV (Figure 4). It can be transported on board a HMMWV, towed by other vehicles, or driven either by an onboard driver or under remote command and control. It also can be air-transported by rotary- and fixed-wing aircraft.

Figure 4. STV

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2 The demonstration and validation phase of ASD requiring manufacture and development, test and evaluation (DT&E) of engineering prototypes.

Structurally and functionally, the STV represents the four major components of the TUGV: (1) the MBU, (2) the OCU, (3) data communication links, and (4) a RSTA module or other modular mission payloads.

- The MBU is a six-wheel-drive, all terrain vehicle. It contains all automotive and navigational components, including sensors and controls for teleoperated driving under day, night, and adverse weather conditions. A Global Positioning System (GPS) and odometry provide location and direction of travel. The platform is powered by a hybrid 25 horsepower (hp) diesel engine and a 3 hp electric motor for quiet locomotion and operation. Under diesel power, the STV can traverse roads at 35 miles per hour (mph) and travel off-road at 25 mph. The sensor and antenna platform can be elevated to about 5 meters above ground level. The STV's hierarchical architecture, designed for information processing at a number of levels and for add-on of processing power, will allow incorporation of increased machine autonomy as appropriate software becomes available. This architecture was originally developed and adapted for UGV control by the National Institute of Standards and Technology (NIST).
- The OCU is a man-portable monitor and control console equipped with appropriate control interfaces, power supply, processor, and communication links. The operator receives video, audio, and vehicle status information from the MBU location and remotely controls the MBU and mission modules.
- The RSTA mission module consists of a suite of sensors used for both driving and RSTA. It includes day and night television cameras, forward-looking infrared (FLIR), laser range finder and designator, and acoustic sensors. Incorporation of an NBC detection system is planned.
- The STV has redundant video data communication links, a FO cable and a wide-band (line-of-sight) RF link.

The STVs will be used throughout FY 1993. Two of the 14 STVs are being used for safety and technical performance tests. The remaining vehicles are undergoing a series of operational tests to validate and refine the operational employment concepts and performance requirements for the TUGV. A concept of employment evaluation (COEE) simulating operational scenarios was conducted at Fort Hunter-Liggett, CA, during February and March 1992. This test series, with soldiers and marines participating, will continue throughout 1992, culminating in an early user test and evaluation (EUT&E). These events will provide the user with hands-on experience for developing operational tactics, techniques, and procedures for TUGV employments and for refining the final Operational Requirements Document (ORD).

Based on the result of this test series and DEMO I, selected technologies will be integrated into the candidate TUGV platform(s) for the DEMVAL program. To reduce development risk, the resulting prototypes will be required to demonstrate that all the teleoperation/teleassistance technologies necessary to meet the operational performance requirements are mature enough for a Milestone II decision.

3. Program Schedule and Funding

The overall program schedule and the funding levels for the TUGV project are shown in Figure 5.

		FY90	FY91	FY92	FY93	FY94	FY95	FY96	FY97
Schedule	Milestone II					△			
	DT&E								
	OT&E			COEE	EUT&E				
	Milestone III								
Funding ($K)	OSD	6700	7650	8100	7800	6000			
	Army					6000	6300	6500	6800
	USMC					5000	1400	2000	2500

Figure 5. TUGV Program Schedule and Funding

The TUGV DEMVAL will start in FY 1993 after approval of the ORD and continue into FY 1994. DEMVAL does not require the development of either a new platform or new technologies, only their integration into the TUGV prototype. Hence, a Milestone II decision is planned in FY 1994. Completion of the TUGV EMD is planned for FY 1998.

The TUGV ASD is completely funded through the Robotics Program. The Army and Marine Corps provide EMD and production funding roughly in proportion to their anticipated TUGV procurements. Currently, about 1,200 TUGVs are planned to be procured.

C. RAPID RUNWAY REPAIR (RRR)

To sustain offensive and defensive air operations, it is essential that the runways from which the planes take off and land remain intact. Restoration of airfields following enemy attack is an Air Force requirement; air bases must be available for flight operations

within mission time requirements. However, dangerous post-attack conditions complicate runway repair. Subsequent attacks may occur; the enemy may scatter mines during initial or follow-on attacks; the threat of lethal chemical and biological agents is increasing. These hazardous conditions inhibit manned runway repair operations and also require additional manpower and equipment for backup support. Under these conditions the current method of restoring the operational capability of airfields is both manpower-intensive and unable to complete the task within the time required.

The RRR UGV (Figure 6) provides a teleoperated/robotic means of executing runway repair and recovery, including cleanup of unexploded ordnance. Under post-attack conditions, remote operator(s) and other airbase personnel can remain at a safe distance. Based on preliminary performance tests of a brassboard design, it is estimated that these remotely operated machines working alone will decrease crater repair time by 35 percent compared to manned systems. Thus RRR responds to safety, manpower, and mission time requirements.

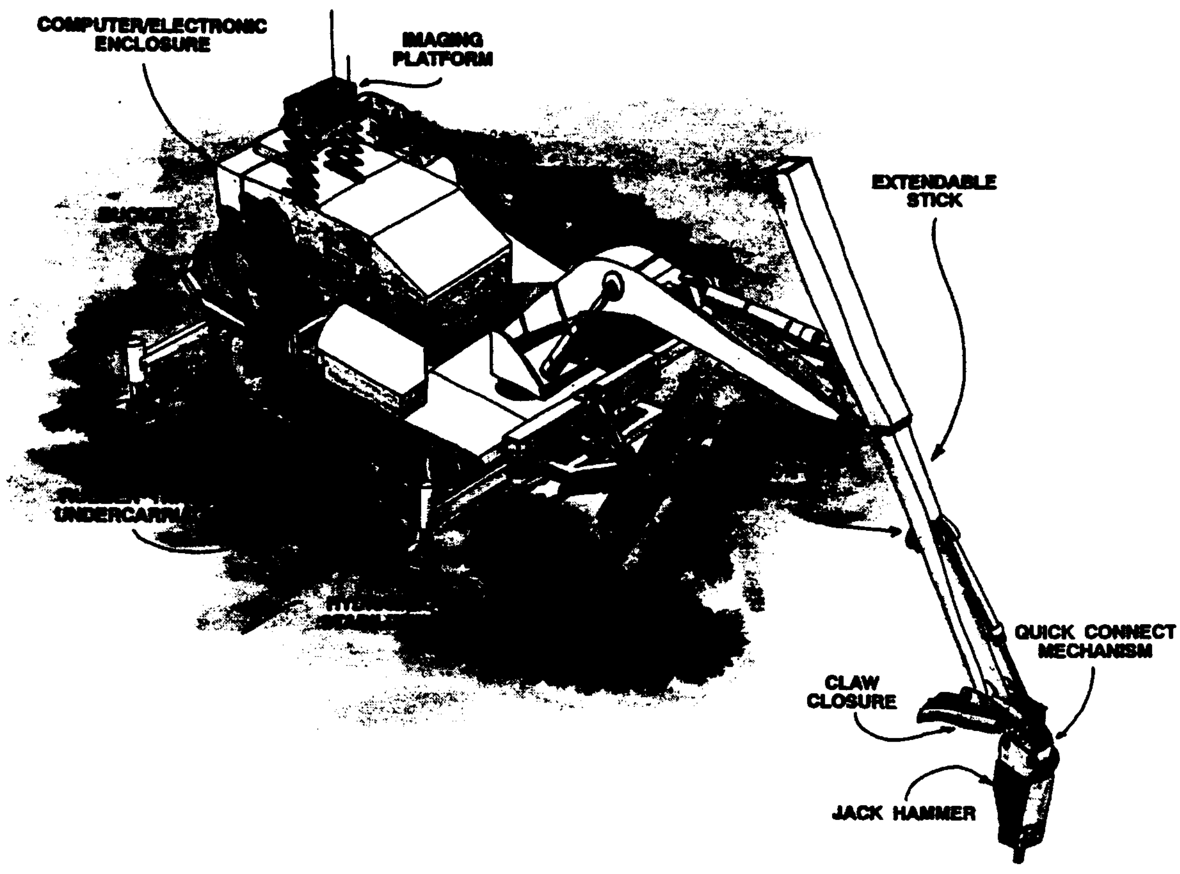

Figure 6. RRR--Conceptual Design

1. System Description

The RRR UGV will weigh less than 50,000 pounds--compared to 60,000 pounds, for the current human-operated excavator--and will be designed as a construction robot for multi-purpose use and for rapid air and ground transportability. The RRR robotic system consists of a central control facility (CCF) and multiple mobile repair platforms. Communication is through a wireless RF link with an umbilical FO link as backup. The CCF, which can supervise 25 platforms concurrently, includes the communication transmitter and receiver, display monitors, and controls for the various RRR mission functions. The platform is a tracked UGV and is equipped with a communication transmitter and receiver, stereo video cameras [color as well as infrared (IR)] for navigation and engineering tasks, a laser scanner, VME[3] electronics for automotive functions, a high performance processor, an inertial/GPS navigation system, and an effector system with robotics tool exchange for the various engineering tasks. The latter includes a 30-foot reach multi-function arm equipped with position and force sensors for manipulator control. The RRR UGV has a 295 hp diesel engine that powers the automotive system and the hydraulic system of the effector arm and provides electric power for the onboard electrical and electronic systems. System operability in adverse lighting, weather, and ground environments will match or exceed manned construction equipment.

2. Technical Program Plan

The RRR ASD is being carried out in three phases shown in Figure 7. Each phase leads into a decision gate at which acquisition critical technologies and performance criteria must be met before the program can progress into the next event. The first phase is complete. To reduce risks, critical component technologies were identified early and tested using available engineering construction vehicles modified for unmanned operation: a John Deere 690C excavator and mule, a four-wheel navigation testbed. In coordination with the other robotics projects, especially DEMO I, a series of technical assessments were conducted for each critical component technology before the overall system design and program road map were established.

3 Versabus Module European, an electronics interface standard.

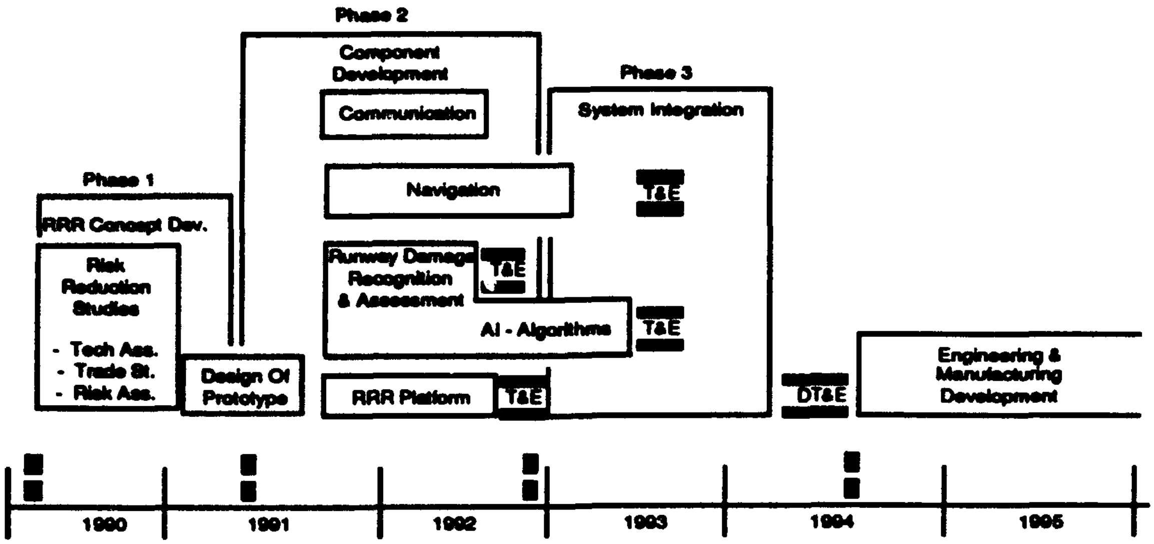

Figure 7. RRR--Demonstration and Validation Phase Events

The RRR program is now in phase 2. It focuses on component development for communication, navigation, runway damage detection and assessment, automotive and mission effector components designed for robotic use, control architecture and information processing hardware and software, and system integration. Each developed component will undergo technical and operational performance testing and evaluation before proceeding into the integration phase. Each component area is described below:

- Communication--Using a fixed OCU and the John Deere excavator, the performance of candidate communication links and protocols will be tested and evaluated for RRR missions, under teleoperation and supervised robotics control. Protocols and associated hardware were developed by NIST and are also being applied to the TUGV. The performance demonstration is planned for September 1992.

- Navigation--Performance tests and analyses of navigation subsystems, some of them derivatives of DEMO I, will be carried out over a 12-month period. These subsystems include sensor-based obstacle recognition and avoidance (taken from the TUGV project), computer-aided remote driving based on GPS and odometry, and route retrace and retrotraverse (with and without path off-set). Subsystems will be selected for inclusion in the RRR navigation system. Demonstration of the integrated system is planned for August 1993, using the mule.

- Runway Damage Recognition and Assessment--This function requires three-dimensional information about the runway in front of the RRR UGV. Possible sensors include stereo vision or a combination of an imaging system and a ladar. The machine intelligence technology base for handling this mission task at the robotics level of autonomy is being developed by DEMO II but will not

be available for RRR use within the component development phase. Hence, performance demonstration of a hybrid man-machine solution is planned at the end of FY 1992.

- Automotive and Mission Effector Components Designed for Unmanned Use--The RRR demonstration platform is now being built and will be delivered by mid-FY 1993. Demonstration of teleoperational navigation and flexible all-around construction capability is planned for November 1992. A major part of the software that controls engineering repair tasks has been developed and tested on the John Deere excavator.
- Control Architecture and Information Processing Hardware and Software--The NIST real-time control architecture was selected for the RRR. All system components are being designed for incorporation into this control system. The onboard processor will be selected after the specification of the critical system components and their computational requirements is complete. Since software development and check-out is an integral part of the communication, navigation, and mission component developments, no specific demonstrations of control architecture are scheduled in phase 2. Demonstration of overall system performance is planned for August 1994, as part of phase 3 of ASD.
- System Integration--After integration of the selected components into the control architecture and onto the new platform, the resulting engineering prototype will undergo an intensive DT&E. A crater will be blown in the test runway and the RRR UGV will have to carry out the crater repair. This involves navigating under supervisory control from a central assembly area to the approximate location of the crater, finding the crater on the runway, mapping the crater and assessing the damage, determining the repair sequence, executing the repair, and returning to the assembly area. Final system performance demonstration is scheduled for August 1994 at Tyndall Air Force Base, FL.

The system integration phase will conclude with a technical and operational performance review of the RRR engineering prototype to determine whether the RRR program is ready for Milestone II.

3. Program Schedule and Funding

The RRR program was initiated in March 1990. The Air Force's requirement for rapid deployment is being implemented in the prototype design. In November 1991 a contract was awarded to Eagle-Picher Industries, Lubbock, TX, for design, development, and fabrication of the RRR prototype platform, which will be available in FY 1993. The various system components being developed will be integrated into this platform. DT&E

of the resulting RRR engineering prototype is planned for the second half of FY 1994. Currently, Milestone II is planned for the end of FY 1994, with EMD to be completed in FY 1997. Figure 8 shows the schedule and funding for RRR by fiscal year (FY 1990 - FY 1997). Currently, procurement of about 125 RRR UGVs is planned.

		FY 90	FY 91	FY 92	FY 93	FY 94	FY 95	FY 96	FY 97
Schedule	Initiation	▲							
	Milestone II					△			
	DT&E			▭	▭	▭		▭	
	OT&E							▭	
	Milestone III								△
Funding ($K)	OSD	750	2000	2000	1500	1000			
	Service	250	375	325	300	300	600	3400	2900

Figure 8. RRR Program Schedule and Funding

D. REMOTE ORDNANCE NEUTRALIZATION SYSTEM (RONS)

The RONS is being developed in accordance with the Joint Service Operational Requirement for RONS of 26 February 1990. RONS is now in ASD. When fielded in the late 1990s, it will replace Service-peculiar teleoperated EOD systems that have extremely limited operational capabilities and utility. The RONS platform will separate the EOD operator safely from accident/incident sites where explosive, chemical, and radiation hazards are present. This new system will provide EOD personnel with a means to secure unexploded ordnance, attach a render-safe tool, withdraw to a safe area, and fire/function the tool.

1. System Description

The RONS consists of the operator controls, a mobile platform (see Figure 9), a closed-circuit color television system, a dual RF and tethered FO communication link, required power source, and a manipulator arm with end effector that uses various tools.

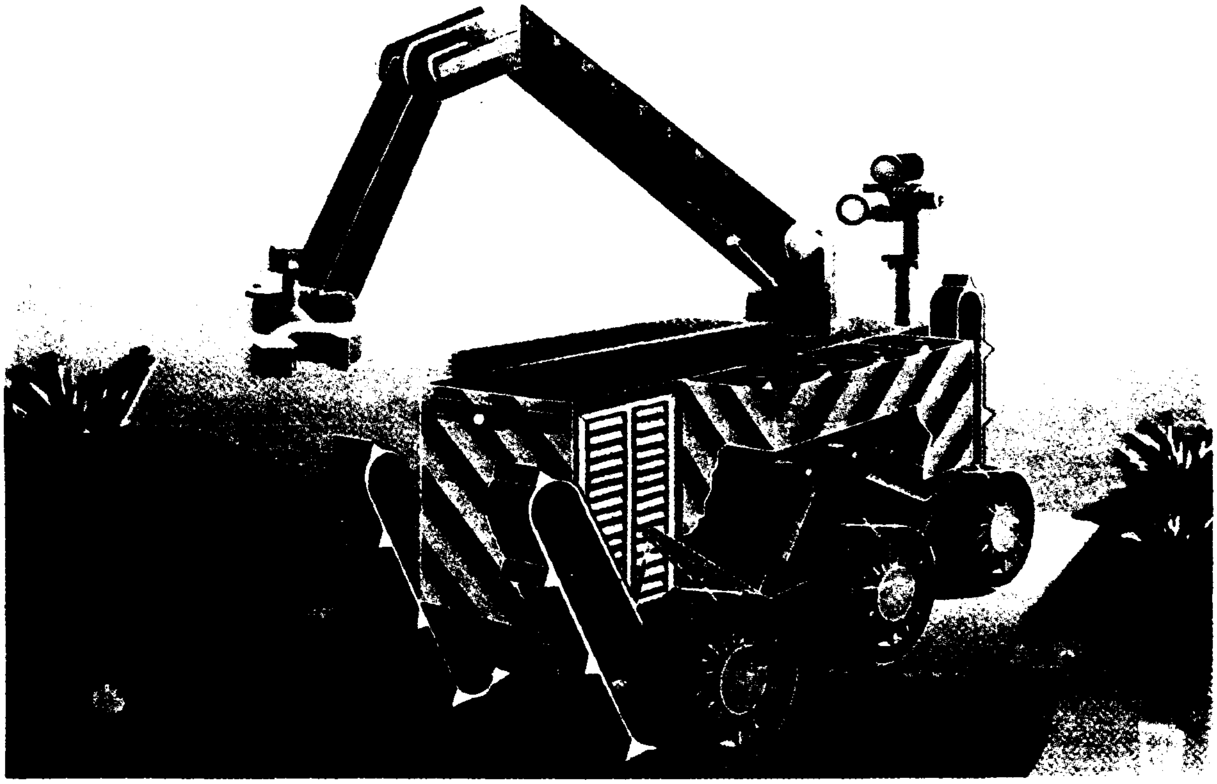

Figure 9. RONS Exploratory Development Prototype

The control console includes the RF and FO communication transmit and receive interface, television display monitor, power converter, and electronics for mobile platform control and telemetry. The mobile platform is equipped with a removable closed-circuit television camera with zoom lens (capable of both color and low-light-level black and white), removable video lighting, RF and FO communication transmit and receive interface, and associated electronics. The FO tether enables system commands and sensor data to be passed between the mobile platform and control console when RF communication is not possible or not desired. RF communication may be encrypted for security and safety reasons. All (control, video, audio, and system status) data will be transferred digitally for direct digital data storage and processing. A lightweight diesel engine will supply power for operational functions. The platform is designed for low velocity driving in a wide spectrum of operational environments. The RONS will be operable under bad weather conditions.

The RONS UGV will have a highly versatile seven-function manipulator equipped with a triaxial wrist assembly. The manipulator will have an operational envelope of 6 feet above the ground, 3 feet from all edges of the platform, and 2 feet below ground level at the outer operational perimeter. Tools can quickly be changed robotically via a master control. Using changeable grippers, the manipulator will be able to grasp a variety of

typical ordnance/explosive device configurations. The tools will be both man and machine emplaceable. They are stored on the platform in a secure holster until needed by the arm or released by the operator for man emplacement. Tool requirements include a .50 caliber dearmer, rocket and mechanical impact wrenches, and various common hand tools.

2. Technical Program Plan

To reduce risk, the program initially pursued two acquisition concepts: a system integration of NDI components and a new system development. The first was discontinued due to the complexity and cost of integrating major commercial subsystems into a system that only partially would meet RONS's operational requirement. The second effort consisted of a series of design trade-offs and risk analyses. This resulted in a system design that makes significant use of commercially available components, exploits the teleoperation technologies recently developed by the DoD robotics program, will meet the operational requirement, and can be developed within budgetary constraints.

Figure 10 shows the technical road map of RONS's demonstration and validation phase.

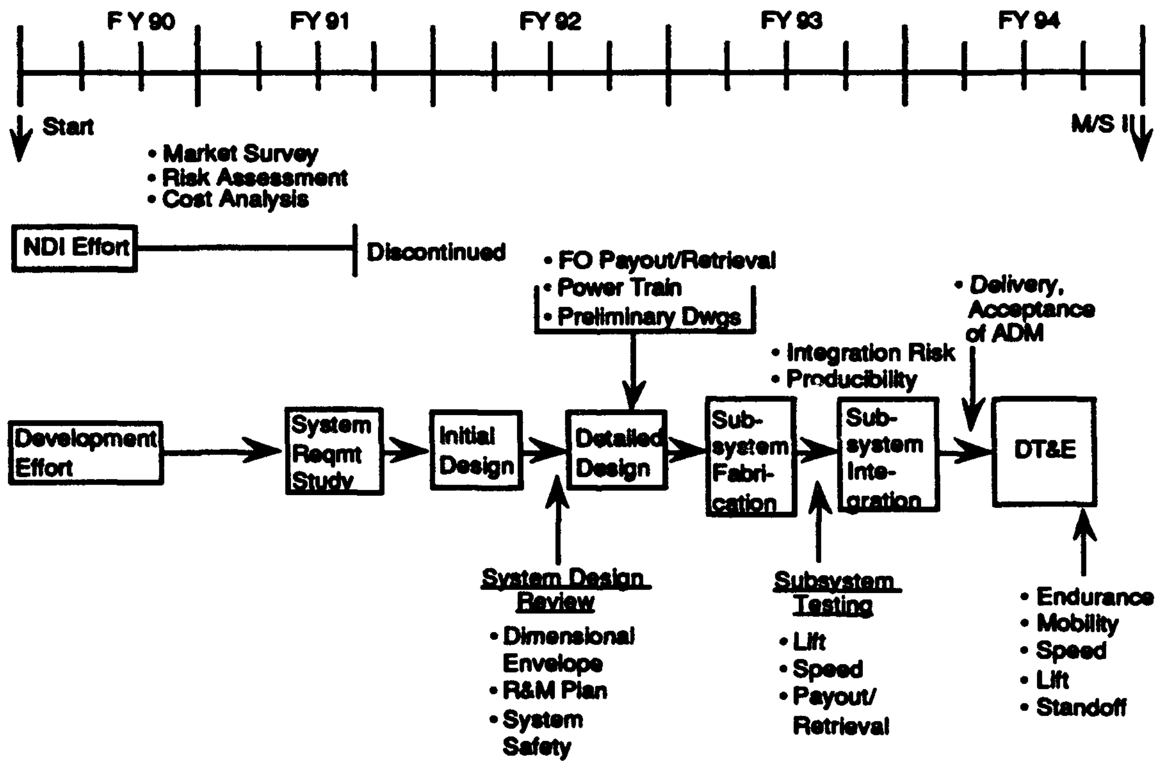

Figure 10. (U) RONS--Demonstration and Validation Phase Events

Before advancing to Milestone II, the following critical technical performance requirements must be demonstrated:

- Endurance--RONS must be able to operate continuously for 6 hours using the diesel engine and for 1 hour relying only on the battery system.
- Dimensional Envelope--RONS must be able to maneuver through a 30-inch-wide opening and negotiate turns from the 30-inch opening to a 48-inch-wide hallway.
- Mobility/Speed--RONS must be able to make left and right 90° neutral turns at forward speeds up to 3.5 mph and reverse speeds up to 3 mph and to climb and descend 45° stairs and a 20 foot high, 45° grass-covered slope.
- Manipulator Performance--RONS must have a lift capacity of 100 pounds and all required EOD manipulator functions must work properly.
- Remote Command and Control--RONS must operate with up to 1,000 meters separation between the operator and the platform.

3. Program Schedule and Funding

The RONS program was initiated in March 1990. In June 1991, a contract was awarded to Battelle, Pacific Northwest Laboratories, Richland, WA, to design, develop, and fabricate an advanced development model (ADM). The functional baseline configuration was established in November 1991. Subsystem development is now underway with system integration commencing in July 1993. The Milestone II decision for proceeding into EMD is planned for April 1994, with EMD to be completed in FY 1998. Figure 11 shows the schedule and funding by fiscal year (FY 1990-FY 1998). Currently, procurement of about 200 RONS UGVs is planned.

		FY90	FY91	FY92	FY93	FY94	FY95	FY96	FY97	FY98
Schedule	Initiation	▲								
	Milestone II					△				
	DT&E				□		□		□ Techeval	
	OT&E								□ Opeval	
	Milestone III									△
Funding ($K)	OSD	800	700	1700	1600	1500	0	0	0	0
	Service			400	900		1100	1100	1100	1100

Figure 11. RONS Program Schedule and Funding

E. UGV TECHNOLOGY ENHANCEMENT AND EXPLOITATION (UGVTEE)

Current and future UGV acquisition projects are supported by a program to mature those technologies that are critical to the automation of UGV systems. Presently, this program has two parts. The near- and mid-term part, DEMO I, focuses on providing the mission capabilities and technological enhancement required for the TUGV program and for the narrower applications of other UGVs. DEMO I reached a milestone in April 1992 with an ambitious series of demonstrations at Aberdeen Proving Ground (APG), MD. The long-term part, DEMO II, focuses on artificial intelligence and robotics to enhance operational capability. DEMO II, now in its second year, builds on the advances of DEMO I. It emphasizes autonomous navigation under battlefield conditions, RSTA functions while the UGV is moving, automated communication with other vehicles, and workload partitioning between vehicles to accomplish mission objectives. Table 1 above shows planned funding for UGVTEE.

1. DEMO I--Technology for First Generation UGVs

Although teleoperation has advantages, without sufficient automation it has serious disadvantages that include:

- Overburdening of the operator
- Precluding multiple vehicle control by a single operator
- Requiring wide bandwidth communication.

To alleviate these disadvantages, which are operationally limiting, a technology thrust was initiated in FY 1990 for the first generation UGVs.

The main objective of DEMO I is to accelerate the maturation of the most critical teleassistance technologies and to demonstrate--in realistic system configurations--their readiness for acquisition programs. The emphasis is on reducing operator workload. In particular, DEMO I has investigated five technology areas in order to provide component technology for integration into the TUGV DEMVAL prototype.

- Navigation--The effects of high and low data rate operations on full-time teleoperated and supervisory control for day and night operations; automated mobility modes such as road following, path retrace, and limited obstacle detection and avoidance
- System Control Architecture--New options for UGV control through integration of teleoperated and robotic control modes

- RSTA Mission Package--Adaptation of general RSTA algorithms for UGV use and remote operation; mission package performance assessment
- Communication--The relative utility of various narrow and wide bandwidth communication alternatives
- Human Factors--Effects of man-machine interface on operator workload and performance.

Figure 12 shows the overall structure of DEMO I. Candidate technologies were identified in FY 1990. This was followed by component development, testing and evaluation on the basis of which components were selected for system integration. The DEMO I hardware and software components are now operational. Their performance was demonstrated to DoD decision makers and to the national robotics RDT&E community 28 April to 8 May 1992 at APG. The developed technologies and associated test and analysis results are being documented to facilitate transfer to ongoing and future robotics programs.

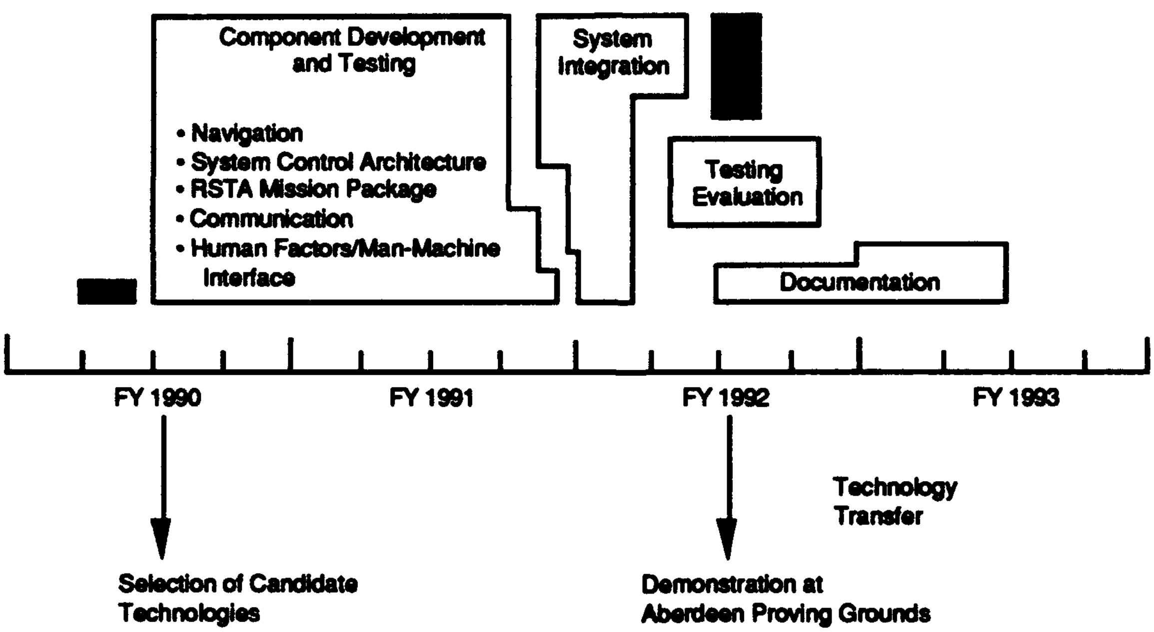

Figure 12. DEMO I Program Overview

Figure 13 shows the pictures of the six HMMWV test vehicles used and two scenes during the conduct of the test.

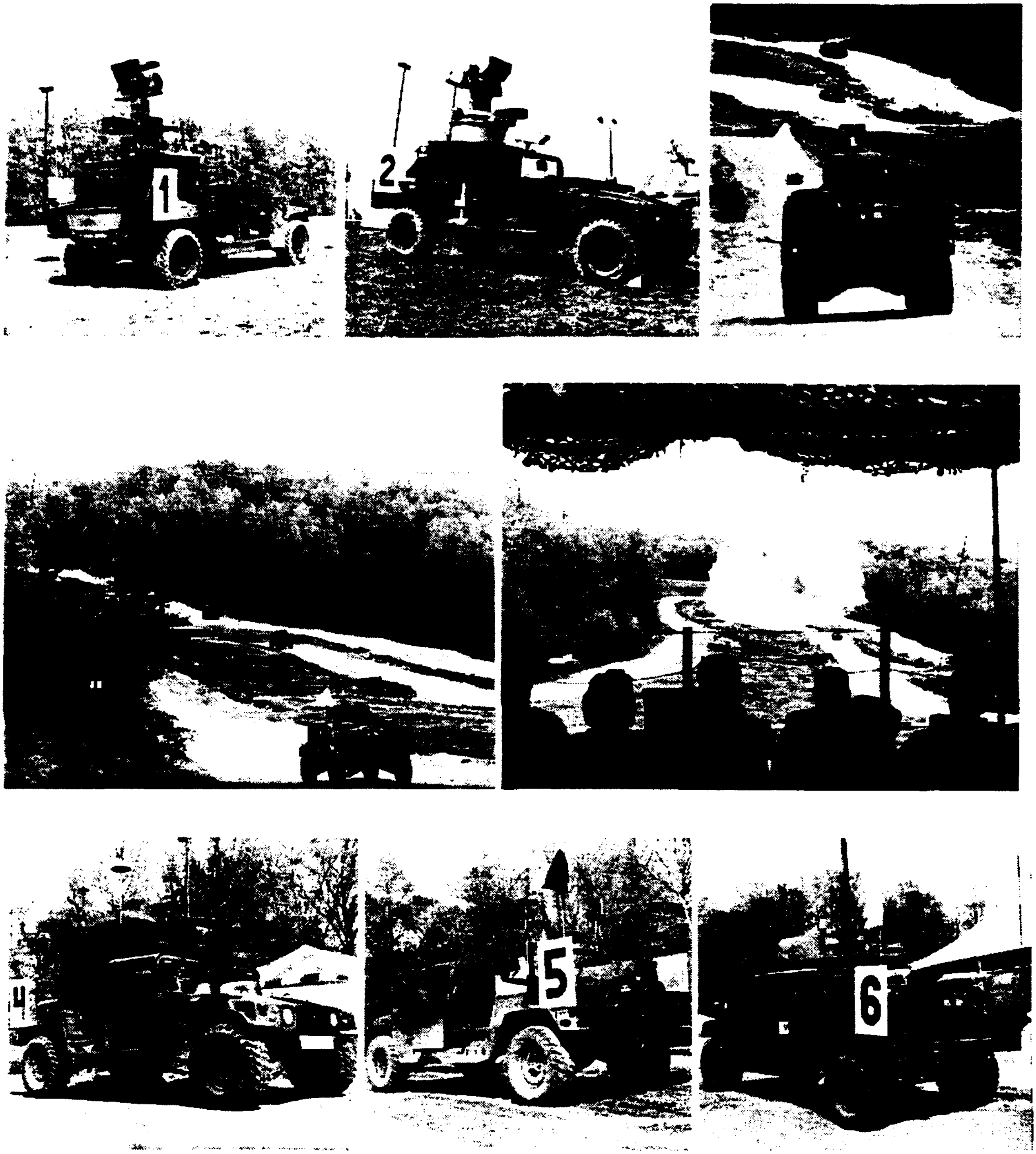

Figure 13. DEMO I--Performance Demonstration, 28 April to 8 May 1992, Aberdeen Proving Ground, Maryland

a. Accomplishments

The following sections describe the technical achievements of DEMO I in terms of the background, objectives, accomplishments, and potential applications to ongoing and future acquisition programs.

Navigation. In 1990, teleoperation required wide bandwidth communication and continuous operator control and execution of all vehicle functions, including navigation and driving. Presenting the local environment as seen by the UGV sensors to the operator in real time makes RF communications impractical. Hence, UGV acquisition programs, tended to rely on FO tethered communication, which seriously impedes mobility.

Two sets of navigation objectives were set for DEMO I:

- Allow teleoperated driving via narrow bandwidth data transmission by developing appropriate data compression and spline driving techniques.
- Building on earlier technology base work, introduce autonomous conduct of certain types of driving such as path retrace and retrotraverse, road following, and limited obstacle detection and avoidance.

Current Status and Results. The underlying algorithms and executing software, including interface with sensors and actuators, have been developed and demonstrated for spline driving and certain autonomous driving modes.

Two methods of local spline driving, CARD and the Feedback Limited Control System (FELICS), have been demonstrated. CARD was originally developed for interplanetary control of UGVs to overcome communication time delays. Its adaptation for military use allows the operator to view a single stereo image of the local environment, review it, and select an obstacle free, drivable path to the next destination point. The path instructions are relayed to the UGV as a series of way points and executed by the UGV navigator. When the destination point is reached (or if a nontraversable obstacle is encountered in the programmed path), the UGV stops. However, as long as the path is updated before the destination is reached, the driving is continuous. CARD navigation has demonstrated an accuracy of less than 1 meter over a 100-meter path. CARD also allows the UGV to traverse a path segment during which communication is interrupted, if a high accuracy map of that segment is available. FELICS is a proprietary teleoperation driving system, in which the operator continously drives a "puck" on the screen that leads the UGV. Its algorithms have demonstrated effective driving with video data of less than one frame per second with minimal onboard data processing.

The autonomous navigation packages developed in DEMO I encompass road following, path retrace, and path retrotraverse with automated turnaround and backup. Autonomous road following uses algorithms to extract road edges and demarcation lines from the navigation camera images and to keep the vehicle positioned in the center of the lane. The speed is set and controlled by the operator; 20 kilometers (km) per hour on roads with a 50-meter turn radius has been demonstrated. Path retrace and retrotraverse rely on non-visual navigation information collected by GPS and inertial sensors during a previous path traverse (manned or teleoperated). With this information the path can be traversed again in either the forward or backward direction. In case of video communication loss due to terrain conditions, path retrotraverse, which includes autonomous turnaround, allows return to a location where communications can be reestablished.

Current capability for obstacle detection and avoidance is limited to avoiding collisions with large objects that appear in the driving path. The obstacle is detected either acoustically or through low-power millimeter wave (MMW) doppler or through stereo vision and the UGV is brought to a stop. It remains stopped until the obstacle disappears or new navigation instructions arrive from the operator.

An automotive control system for the HMMWV chassis was developed with greatly improved response time, electric motor steering actuation, and sensor-feedback control of acceleration and braking. This system allows quick conversion between unmanned and manned operation--a requirement for most UGVs.

Application to Acquisition Programs. The DEMO I navigation algorithms were developed with the TUGV application in mind. They substantially improve the TUGV operational navigation capability. Automated return from mission via the previously driven path frees the operator for other tasks, allows recovery of the FO cable, and enables the UGV to return when communication is severed. With path retracing, a previously driven route can be repeatedly traversed without an operator, and tasks, such as laying a smoke screen where visibility is poor, can be executed. Spline driving permits the use of wireless tactical communications (SINCGARS) as a video link for teleoperated driving and thereby increases the battlefield mobility of the UGV.

DEMO I navigation technologies can also be tailored to other UGV applications. Because RONS will be transported close to an EOD site and then driven slowly to the actual EOD site, wide bandwidth communication and teleoperational control can always be assured, even in buildings. Hence, the operational need for teleassisted navigation technologies is minor. However, autonomous path retrace and retrotraverse software may

be incorporated into the RONS OCU to bring the UGV back after completion of its EOD mission, thereby reducing operator burden.

In contrast, operational requirements for RRR emphasize robotic levels of autonomy. Because the RRR mission is confined to airfields, precise navigational information can be acquired before the RRR's employment. DEMO I navigation technologies can be combined into a navigation network that uses rote robotic driving with intermittent human oversight to guide the RRR to any spot on the airfield. Pathways may either be preselected or controlled by the operator. Implementation of this approach requires some modifications of the technology packages to increase their versatility, e.g., autonomous path retrace and retrotraverse with the additional ability of driving with parallel offsets to the reference path and of going around readily recognizable obstacles such as aircraft or vehicles.

The navigational context for UGV applications to environmental restoration and to exterior physical security (see Section F below) could be quite similar to that of RRR. For physical security, information on all patrol paths can be collected in advance and various DEMO I technologies synthesized to achieve highly automated navigation. Path randomization might be required but should not be difficult. However, in some applications the UGV will be required to operate in traffic and obey traffic laws. Automation of this type of operation is being developed in DEMO II but is not yet ready for application.

System Control Architecture. A real-time control system (RCS) architecture whose prior evolution includes application to industrial robots and space exploration systems and successful adaptation to various UGV programs was selected for the DoD robotics program. This RCS architecture controls all vehicle mobility and payload functions and coordinates the operations of all subsystems on the UGV including communication with the operator control station. RCS is judged to be the best candidate because of its hierarchical functional structure and demonstrated performance. Moreover, under the coordination of NIST, the RCS architecture has gradually evolved into a national, standardized system control architecture for robotics.

The objective is to adapt the RCS architecture for first generation UGVs, which require a control architecture merging teleoperation and supervisory control.

<u>Current Status and Results.</u> Through collaboration with NIST, a supervisory control architecture for UGVs is now available that integrates system subfunctions

operating at widely different levels of autonomy, pure teleoperation to pure subfunction autonomy, and that is transparent to the operator. (Extension of the RCS to UGVs that operate more autonomously in a battlefield environment is included in DEMO II.)

Application to Acquisition Programs. This RCS architecture is being implemented in the TUGV and RRR and is intended for use in new DoD UGV developments.

RSTA Mission Package. The UGV program is using sensors developed for other applications. For the RSTA mission, suitable algorithms and software for sensor and weapon control and for aided target recognition and acquisition were not available in 1990. However, previous work in automatic target recognition and automatic target cueing (ATR/ATC) for manned systems provided a foundation.

DEMO I was given two RSTA objectives to be met within the TUGV program time constraint:

- Provide an ATR/ATC capability that supports teleassisted RSTA for the TUGV
- Develop an operator controlled, automatic target tracking and weapon aiming capability and verify the algorithms and software using a laser designator.

Current Status and Results. A RSTA mission module was developed and fully integrated into the UGV architecture. It incorporates:

- Passive sensors--Imaging black and white TV and 3 to 5 micron FLIR with electronic pan/tilt control and an acoustic sensor array.
- A laser range finder for measuring distances.
- A turret control system for pointing an effector, e.g., laser designator or direct fire weapon, at the centroid of an object with an accuracy of 0.1 milliradian (mrad).
- Video processing for ATR/ATC that computationally stabilizes the ..nage, preprocesses the data, detects scene changes caused by object motion, extracts the object from the scene, determines its characteristics, compares these with target files for identification, and brings the result to the operator's attention. A similar package exists for the acoustic sensor array allowing detection, classification, and determination of direction of acoustic sources.
- Software that tracks moving targets and, after operator authorization, performs effector aiming and firing.

All of these capabilities were demonstrated in DEMO I.

Application to Acquisition Programs. The primary application of the advances in RSTA automation achieved in DEMO I is to the TUGV. Though rudimentary in comparison to human capabilities or to the potential of more advanced algorithms operating on high performance computers, the DEMO I algorithms provide an important improvement in automation compared to current manned vehicles. Hence, they will reduce operator workload significantly in conducting the TUGV RSTA mission.

The RSTA technology is potentially applicable to a variety of surveillance applications such as physical security and border control. In these applications, the effector technology may also be applicable depending on the requirements for system response to intrusion.

Communication. Unassisted teleoperation places a significant requirement on the capacity of the communication system. FO and wide bandwidth RF are used extensively to transmit video in real time. Narrow bandwidth RF can also be used for video transmission but at a much lower data transfer rate. Each of these technologies has significant limitations for military operations that usually require low detectability, robustness against countermeasures, security of information exchange, timeliness of transmission, NLOS capability, unrestricted force mobility, and, for RF, shared use of allocated frequency bands.

FO communication satisfies these requirements except that, for general tactical UGV applications, it impedes force mobility because of the FO umbilical cord. This is less important for some specialized mission tasks. Greater ruggedness of the FO cable and development of an onboard cable retrieval system are needed to adapt FO technology to battlefield use.

Wide bandwidth RF communication is free from physical tethers and provides good quality, video transmission. Line-of-sight (LOS) restrictions, vulnerability/security, and overcrowding of frequency bands are major drawbacks of wide bandwidth RF communication for TUGVs. Narrow bandwidth RF communication, such as the already fielded Single Channel, Ground/Air Radio System (SINCGARS), ameliorates these problems, but its drawback is low data transfer rate.

Three communication objectives for DEMO I were established:

- Improve the battlefield survivability of FO cables and develop a FO cable rewind capability

- Continue to develop a directional wide bandwidth RF data transmission system for multi-vehicle communication
- Develop an image compression/transmit/restoration capability that can be used for teleoperation of TUGVs via low data rate, narrow bandwidth RF links.

Current Status and Results. The FO task was completed in 1991, resulting in a more rugged FO cable and a cable deploy and retrieve mechanism that satisfies the STV and TUGV operational needs.

A multi-vehicle communication system and an associated mobile command, control, and communication (C3) center have been developed. The C3 center is equipped with a directional microwave (MW) antenna system for receiving stereo video and other UGV data; an RF transmitter system for control of the UGVs; and a switching network for the various transmit and receive channels. Each UGV has an omnidirectional antenna for receiving control instructions and a directional transmit antenna that is electronically steered to point at the C3 center, using the command link to track the C3 center. The system provides 16 simultaneous links. Up to four UGVs may be linked to and automatically tracked by one C3 center. Directional video data are transmitted in the gigahertz (gHz) frequency band, thereby avoiding the congested lower frequency bands. Also, the use of low-power directional transmitters facilitates concurrent operation of nearby systems without mutual interference. Compared to a tethered UGV system, this communication concept is very mobile, but it requires LOS between UGVs and the C3 center. Incorporation of SINCGARS is planned for NLOS communication.

DEMO I has emphasized communication technologies for teleoperated driving using narrow bandwidth data transmission. This includes a robust video image compression and restoration technique to allow use of SINCGARS radios and to achieve acceptable operator performance despite the loss of video information. The SINCGARS radio can transmit 16 kilobits per second (kbps), which necessitates a compression of about 4,000:1 for a standard 30 frames per second black and white video, and significantly higher compression ratios for color and stereo color TV.

There are a variety of ways to sacrifice image quality. DEMO I work led to a software and hardware package for video compression and decompression that achieves a data compression of 4,000:1. This package--developed at the Oak Ridge National Laboratory (ORNL)--incorporates the decomposition of the image into spatial-frequency bands with variable degradation/compression factors; foveation to concentrate the best image quality at the center of the operator's field of view with greater degradation in

peripheral areas; and image simulation to smooth interframe discontinuity due to frame rate reduction. Results of human response testing are very encouraging.

Application to Acquisition Programs. Any battlefield communication system for UGVs will involve important trade-offs and compromises. FO communication is mature and offers advantages in capacity and security for the TUGV application. The associated mobility penalty can be ameliorated, to some extent, through a backup RF system and algorithms for specialized autonomous driving modes.

The other DEMO I communication efforts have significantly advanced the technology base. Localized use of directional, wide bandwidth communication has potential application to the TUGV, RRR, and other UGVs, as well as to manned systems.

Narrow band communication based on image compression/restoration is likely to become the primary system for battlefield use. This capability will be pursued by advancing communication technology and by developing greater levels of UGV autonomy in DEMO II, thereby reducing communication requirements. For example, algorithm enhancement for transmission of color and stereo video and hardware improvement for easier integration into UGVs and OCUs are necessary.

Human Factors/Man-Machine Interface. Recognizing that the first generation of UGVs will be controlled primarily through teleoperation, the human factor component of DEMO I was focused specifically on facilitating the introduction of teleassistance and on providing human engineering design information to support UGV development decisions. In a general sense, the entire DEMO I effort has been concerned with the interaction and division of labor between the operator and the UGV.

Three human factors/man-machine interface objectives were emphasized for DEMO I:

- Evaluate the effect of camera position, field-of-view (FOV), monochrome versus color images, single camera versus stereo images, and wide versus narrow bandwidth RF image transmission of the navigation and RSTA imagery on the perceptual performance of the remote human operator, with emphasis on tactical military application
- Evaluate, with respect to operator performance, the man-machine interface of candidate operator display arrangement and formats for navigation and RSTA mission control
- Develop algorithms and associated software to ease operator burden in planning and executing the TUGV mission.

Current Status and Results. The man-machine hardware and software packages developed by DEMO I are operator friendly and considerably reduce the human stress of remotely controlling UGVs, compared to the pure teleoperation. Their capabilities were demonstrated at APG, employing three OCU breadboard configurations--a table top controller, a UGV control testbed (UGVCT), the Jet Propulsion Laboratory (JPL) trailer controller and the FELICS controller:

- The table top controller consists of three interconnected modules: a suitcase controller for driving; a SPARC station and monitor for mission module control, combat information processing, and video display; and the low data rate video system and radio. It allows an operator to drive one UGV under teleoperation control while concurrently monitoring the autonomous RSTA mission function of another UGV or to monitor two vehicles while they are in the RSTA mode.
- The UGVCT is a mobile C3 center. The OCU system is mounted on an armored vehicle chassis and communicates with the UGVs through the multi-vehicle communications system. It allows simultaneous control of up to four UGVs, employing three operators. It has been designed for flexibility and adaptability to incorporate UGVs with increasing robotic capabilities. In the APG demonstration, the UGVCT was used in a stationary mode to control three vehicles simultaneously.
- The JPL trailer controller was used to demonstrate an enhanced CARD package with improved stereo display and operator interface that allows longer path length and faster path completion. This was accomplished using a SINCGARS radio communication link.
- The FELICS controller demonstrated the reduction in operator burden communication requirements that teleassisted operations can provide. FELICS permits the operator to remotely control the MBU by merely steering (via a joystick) an icon superimposed on his video display. The vehicle was effectively controlled with only one video frame every 3 seconds.
- The developed software includes interactive route planning algorithms that allow the operator to derive drivable paths for four UGVs and the UGVCT. These paths guide the actual driving.

Application to Acquisition Programs. Although focused on providing information and tools for the TUGV to facilitate effective man-machine design, the results of DEMO I are widely applicable to other UGV programs. Results pertaining to UGV and OCU design optimization were transmitted to the UGV JPO as they became available. Their documentation for broad distribution is in progress.

b. Summary

Important advances were achieved and demonstrated in each of the five areas of navigation, control architecture, RSTA, communications, and human factors. These advances establish the foundation for a first generation TUGV that relieves the operator of a substantial portion of the workload required for pure teleoperation. For systems that operate in predetermined environments, such as RRR and exterior physical security UGVs, the combination of DEMO I advances can result in a high level of autonomy.

Finally, in addition to its substantive achievements, DEMO I adapted existing equipment, test courses, and expertise to establish facilities for testing UGVs. They provide a readily available infrastructure for diagnostic and performance tests and for the comparison of manned and unmanned vehicles on standardized test courses.

2. DEMO II--Supervised Autonomous Navigation for UGVs

The purpose of DEMO II is to develop those technologies that are critical to evolving UGVs from labor intensive teleoperation to supervised autonomy. DEMO II is exploiting emerging hardware and software advances in passive and active sensing, autonomous navigation, RSTA while driving, high performance computing, and adaptive communication with the goal of demonstrating their maturity for acquisition programs of second generation UGVs by 1995. The technology development and demonstrations for DEMO II will be done mainly on HMMWVs. DEMO II is a four-phase effort, each of which successively demonstrates increased complexity and autonomy of UGV systems. (See Figure 14 for Program Overview.)

DEMO II is now in phase 1. This phase integrates the required mechanical and electrical components, automotive controls, color and infrared visual sensors, GPS, inertial navigation system (INS), odometry, and intervehicle communication. It provides for verification of essential navigation "behaviors," including the basic mobility functions of accurate positioning and semiautonomous path following. After phase 1, the vehicles built for DEMO II will be denoted as Surrogate Semiautonomous Vehicles (SSVs).

Phase 2 will integrate basic map management functions, single vehicle mission planning, off-road and on-road semiautonomous navigation, high-speed capability, landmark detection and identification, and rudimentary behaviors for following rules on the road.

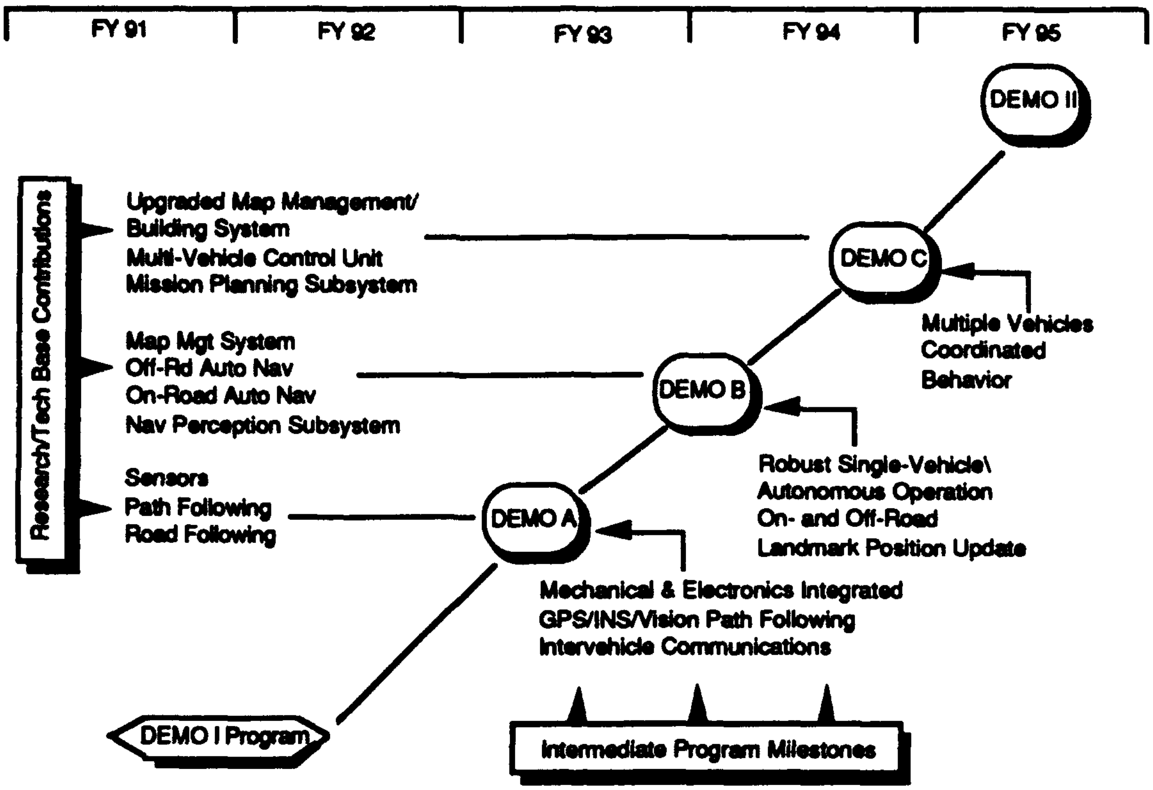

Figure 14. DEMO II--Program Overview

Phase 3 will integrate multiple vehicle control from a man-portable operator control unit, using an updated map management and map building subsystem. It will demonstrate this control with two vehicles executing coordinated, semiautonomous navigation.

Phase 4 will culminate in DEMO II--the second DoD joint UGV demonstration--which is planned for the summer of 1995. This phase will add an automated RSTA subsystem and a multiple vehicle mission subsystem. With this capability a single control unit will be able to operate a team of four UGVs as a screening force. Supervised autonomy of SSVs operating collaboratively will be demonstrated in both offensive and defensive scenarios.

DEMO II is relying on relevant artificial intelligence and robotic technologies being developed at universities for UGV applications. To transition these technologies to the Services and to establish a strong industrial R&D base, each phase is conducted in two steps: first, the individual technology teams integrate the technologies into breadboards at regional sites. After the validation of the breadboard designs, the industry system integrator is responsible for brassboard system integration on the SSVs. As part of this

process, quarterly workshops bring together all program constituents to review work done, resolve problems, coordinate the work to be done, and adjust the program.

Critical capabilities for highly autonomous UGVs were identified at the start of DEMO II. Technological approaches were selected competitively. In some areas, multiple sources were selected to reduce risk and provide technology and cost alternatives. The following paragraphs describe these approaches in six areas: system architecture, navigation, RSTA, high performance computing, communications, and command and control.

a. System Architecture

The architecture must encompass the total system: UGVs, their communication links, and the supervisory command and control. The architecture must handle all mission functions from highly symbolic mission planning down to pixel level processing. The required architecture has been established and is an extension of the NIST RCS architecture, with adjustments to accommodate advanced robotic approaches and partitioning between navigation and RSTA. All technologies going into DEMO II are being developed for this architecture. (See Figure 15.)

The architecture has three hierarchical layers:

- The global action layer contains the "cognitive" functions such as object/target/landmark recognition and route/path/activity planning during mission execution.
- The local action layer contains the immediate behavioral and decision elements that carry out the planning in accordance with the guidelines and constraints from the global action layer. Local action is based on sensor-derived information.
- The control layer contains all "autonomic" functions of the system including the highest rate elements (e.g., servo loop closures and compensations). Processes in this layer tend to operate synchronously.

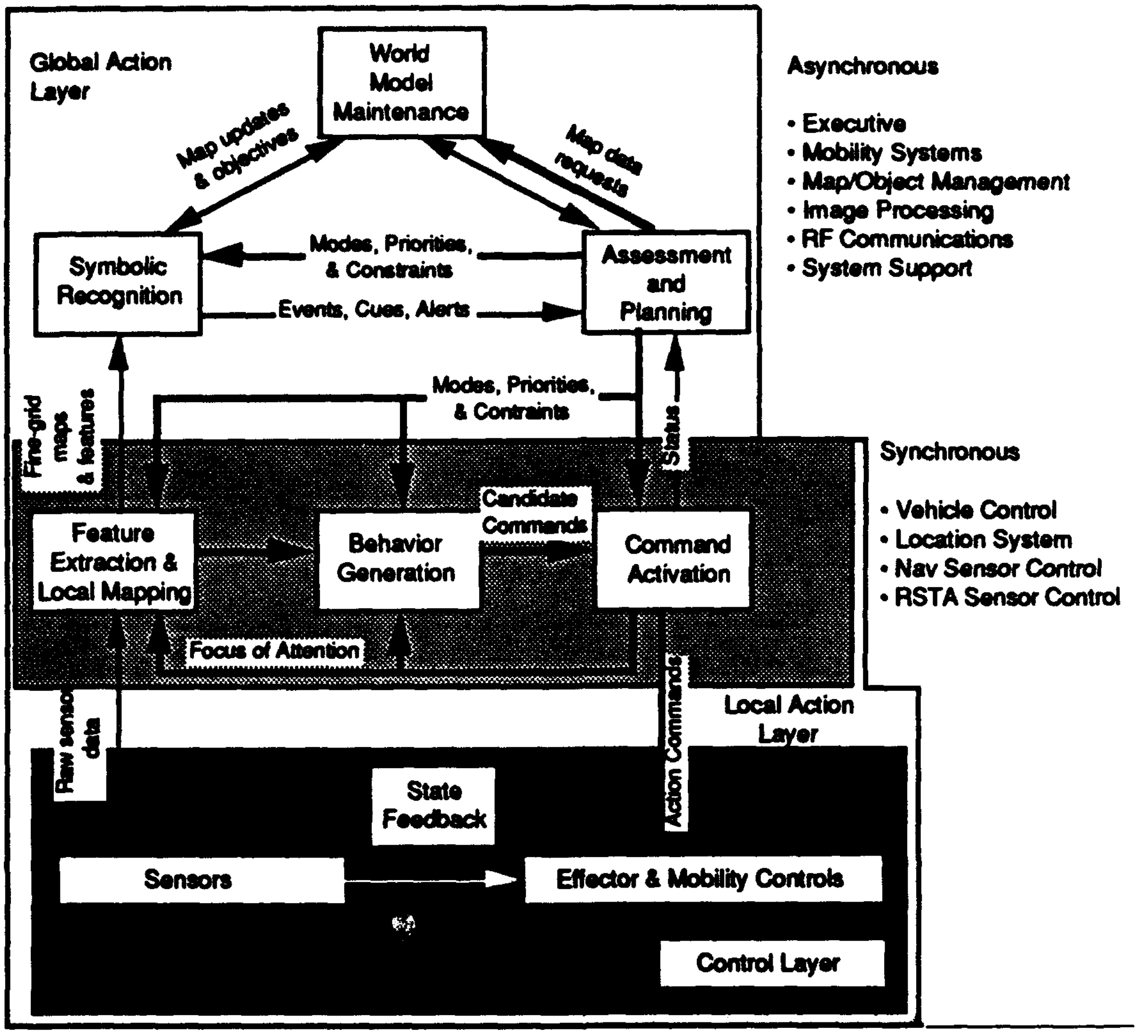

Figure 15. SSV Top-Level Architecture

b. Autonomous Navigation

Figure 16 shows a flow diagram of the autonomous navigation functions being sought in second generation UGVs. (This figure omits the supervisory role of the operator who can monitor navigation performance and can intervene at any time or when requested by the UGV system.) The left column refers to global planning functions. The right columns refer to en route navigation and driving functions.

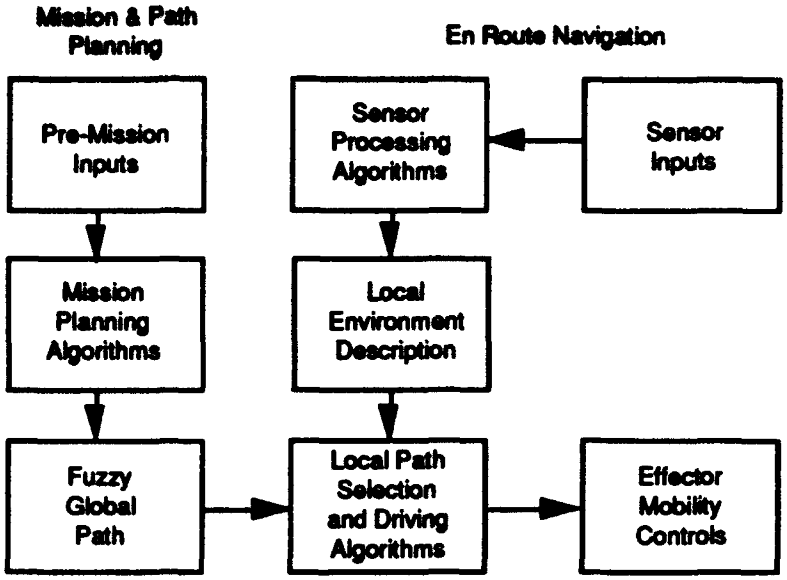

Figure 16. Autonomous Navigation Functions

The navigation segment of mission planning translates information on the mission, cartographic data, the location of friends and foes, and military control measures into an approximate, drivable path for one or multiple UGVs. In addition to this "fuzzy" path on a digital terrain map, the plan includes essential actions and objectives; decision strategies; contingent actions for unplanned events (e.g., cueing supervisor's attention); and interaction between cooperative UGVs. The plan takes advantage of terrain and vegetation to mask UGV movement. The planning algorithms are intended for iterative use, with the human operator revising and supplementing the initial plan by interacting with the algorithms. The operational execution of this path plan is controlled in the global layer of the architecture.

Once the UGV begins to traverse the planned path, autonomous navigation functions depend on sensor inputs, image processing, and AI algorithms to ascertain and characterize the local environment. This includes local three-dimensional map generation from stereo vision and/or interferometry; object and scene identification; landmark recognition; and global and local map merging to upgrade the terrain map and determine vehicle location and orientation.

Local path planning uses the terrain map, the sensed environment, vehicle position, and planning constraints. Driving algorithms include:

- Neural network and feature-based road following that allows the vehicle to travel on multilane paved highways, gravel roads and jeep trails, to traverse intersections, and to recognize road branches

- Road and cross-country navigation based on "fuzzy route driving" instructions with position provided by GPS receivers, inertial measurement, odometry, and landmark recognition
- Obstacle avoidance
- Adjustment of the local path plan to terrain, visibility, path surface condition, automotive and dynamic constraints, and limitations on concurrent processing for navigation and RSTA functions.

The DEMO II navigation sensor package for acquiring the local environment consists of a stereo pair of color cameras, a stereo image IR sensor, and a ladar. Since military vehicles require stealth and low emission observability, one focus of DEMO II is on real-time stereo vision perception and stereo image analysis that overcomes current limitations in the use of stereo vision. The objective is to develop algorithms for passive sensing of the local three-dimensional (3-D) environment for navigation and obstacle avoidance. Algorithms developed for the visible part of the electro-optical spectrum will be extended to the infrared. The ladar provides a secondary 3-D imaging capability that can be used either as a backup or in a hybrid arrangement with stereo vision to resolve ambiguities and refine the spatial resolution of critical sections of the path ahead.

The local navigation instructions are implemented through the effector and mobility controls. This includes control of sensor on/off, pan and tilt, lens and camera adjustments, driving and other automotive functions, manipulators, safety features, and authority limiters.

c. Reconnaissance, Surveillance, and Target Acquisition (RSTA)

If UGVs are to conduct RSTA autonomously, both the extraction of the relevant information from sensors signals and the decision making process must be automated. DoD has been investing heavily in image processing and automated target recognition and the trustworthiness of the extracted information and the decisions that locate and identify potential threats is increasing steadily.

DEMO II is adapting those algorithms that are most suited for meshing RSTA and navigation functions to allow coordinated processing of signals from the optical sensors and adaptive partitioning of the navigation and RSTA processing workload based on the local situation. This will provide RSTA while on the move. Accomplishing this difficult task depends on the processor configuration, capacity, and throughput that will be realized by the Federal high performance computing program.

d. High Performance Computing

DoD has an ongoing R&D program to develop a succession of prototypes of high performance computing systems and associated software and algorithms for military applications. These systems are developed with progressively larger scale, more advanced components, more dense packaging, and more advanced architecture. DEMO II will use the latest prototype that is suited for UGV applications. Phase 3 will include evaluation of the comparative merits of two emerging scalable parallel processors--the Intel/CMU iWarp and the Hughes/University of Massachusetts Image Understanding Architecture (IUA). A first generation iWarp is already operating on NAVLAB-II (Figure 17) at Carnegie Mellon University in support of this program since autumn of 1991. Also, a first generation IUA has been operating at the University of Massachusetts since the beginning of this year.

Figure 17. NAVLAB-II

e. Communication Link

DEMO II will use RF communication hardware and software derived from DEMO I, in particular data compression algorithms, to link UGVs with each other and with the remote supervisor. These links may be direct or indirect depending on the situation. For example, to route the line-of-sight signal path around terrain obstacles, the UGVs will form a communication chain. Architecture and software algorithms for low signature, secure

communications will be demonstrated either with the Packet Radio or, if available, with an off-the-shelf, autotracking, narrow-beam system.

f. Command and Control

All command and control oversight functions will be conducted through an OCU. It will have a simulated display of the area of interest, with direct video overlays from the sensors. The OCU will also have a planning software system with algorithms that establish mission and path plans for the individual UGV using digital terrain and environment maps, and battlefield intelligence. These plans are downloaded to the individual vehicles for mission execution. During the execution, each of the vehicles interacts with the OCU, providing status feedback to the operator.

F. POTENTIAL UGV ACQUISITION PROGRAMS

Except in this section, the UGVMP describes only ongoing robotics projects. This section briefly discusses two potential new robotics projects for which there are immediate needs and which are realizable with demonstrated technology. The first is concerned with exterior physical security, the second with environmental restoration. These two areas have been selected for active investigation.

1. Mobile Detection Assessment Response System--Exterior (MDARS-E)

Current physical security surveillance and enforcement (PSS&E) equipment and methods have serious shortcomings. They rely on human assessment and response, which is labor intensive and exposes personnel to threatening situations. Performance of monotonous PSS&E functions is highly variable and depends on such factors as boredom, fatigue, and conscientiousness.

As early as 1985, an operational and organizational plan for a robotic security system for fixed nuclear and chemical storage sites was approved. In 1989, a program for a mobile detection assessment response system (MDARS) was initiated. Phase 1 of this program has been concerned with interior physical security surveillance and enforcement. The exterior component (MDARS-E) of the program is included in phase 2 and is just beginning.

The MDARS-E system must be capable--under the supervision of a remote operator--of autonomously conducting random surveillance patrols under day, night, and all-weather conditions, responding to security alarm signals, detecting and deterring

intruders, and performing barrier assessment and product loss detection. It must substantially reduce manpower while providing DoD security and law enforcement units with a capability that is at least as good as current manpower intensive PSS&E.

Because of the robotic aspects of MDARS-E, the OUSD(A)/TS and the DoD Physical Security Equipment Management Office (PSEMO) plan to support the advanced system development jointly. OSD program funds will be used for robotics components. MDARS-E development can take advantage of the teleassistance technologies that have been developed by DEMO I and, possibly, early spin-offs of supervised robotic technologies that are being developed by DEMO II. The well-defined, closed environment in which MDARS-E will operate and its relatively rote robotics performance requirements make automation of many functions feasible.

The current MDARS-E concept is based on the use of a military all-terrain vehicle that is common to the Services (e.g., the HMMWV); highly modular system components integrated into a NIST RCS architecture/control system; utilization of components and technologies developed by SANDIA for PSS&E and by the OSD robotics program; and wireless RF communication between the MDARS platforms and the supervisory command and control post.

2. Environmental Restoration

Both DoD and DoE face major cleanup and restoration tasks. The problem has been highlighted by the process of base closings and facility retirements now underway. In addition to toxic wastes, many of our military sites are cluttered with weapon debris, including munitions, whose locations are only vaguely known. Determining the type and extent of contamination and performing the required restoration are time consuming, expensive, and risky to life and health. Requisite special suits, equipment, and procedures increase labor costs and do not completely eliminate the risks. Environmental restoration will require large resources over many years. Diligent use of robotics will help to contain cost and assure safety.

Because many environmental tasks are performed in a confined environment, current and emerging robotic technologies will support the development of highly capable and autonomous UGVs for environmental assessment and restoration. A central data processing system could support a number of UGVs that operate either collaboratively or independently. Different UGVs might perform different functions such as hazard detection, assessment, mapping, civil engineering, EOD, and specialized handling of

chemical or radioactive material. The UGVs could be linked to the control center through a wide-band RF network. Close human supervision or even teleoperational control would be possible whenever necessary. Oversight of autonomous UGV functioning would be the preferred mode especially for repetitive operations.

The first steps in exploiting this opportunity involve determining program priorities and plans and identifying high payoff roles for UGV systems and technologies. This process has been started.

3. Other UGV Applications

A number of other promising UGV applications include the following:

- Countermine, the need for which was reinforced by Desert Storm and its aftermath
- Logistics, for which many functions, such as storage, handling, transportation and distribution, are amenable to automation and robotics
- Border control, which has many similarities as well as some significant differences with exterior physical security.

Prior work and potential new projects in these areas will be reviewed during FY 1993 and promising opportunities discussed in next year's UGVMP.

G. MANAGEMENT RESPONSIBILITIES

In response to Congressional direction, all DoD advanced development projects for unmanned ground vehicles were consolidated in a single program element (PE0603709D) under OSD direction. Responsibility for research and exploratory development remains with the Services and defense agencies. In general, funding of EMD is a Service responsibility.

Figure 18 shows the current OSD UGV program consisting of three 6.3B projects, DEMO I and DEMO II, each of which has been described in earlier sections. Over the past 2 years this program has achieved substantial technical progress and enhanced program coherence.

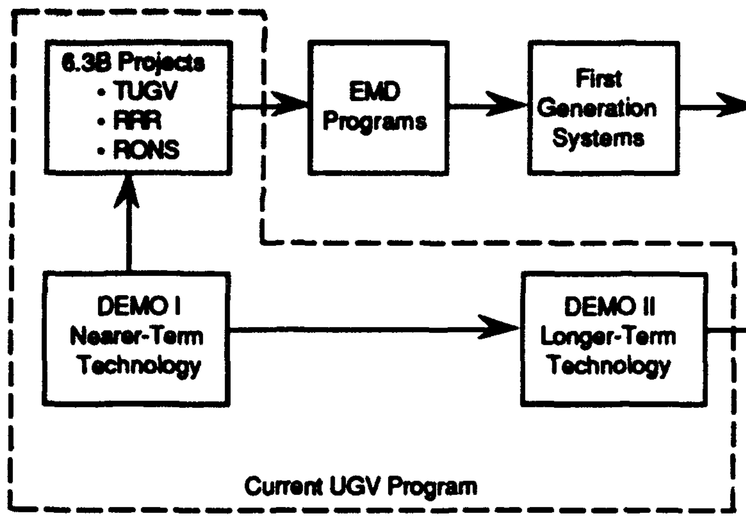

Figure 18. Structure of OSD UGV Program

The Office of the Director for Tactical Systems decides on specific projects within the OSD program, provides program direction, allocates funds to projects and carefully monitors progress. A robotics working group (RWG), chaired by the Deputy Director Tactical Systems (Land Systems), assists in fulfilling these responsibilities. The RWG includes representatives of the Services, DARPA, and other elements of OSD. They provide the information required for program management. The RWG provides a forum for discussing and resolving issues and for transmitting program direction and decisions.

1. UGV Advanced System Development Programs

Day-to-day management of ASD programs is the responsibility of the project managers (who are also members of the RWG) and their staffs.

- Tactical UGV Projects--The UGV JPO is a joint Army/Marine Corps acquisition office with responsibility for land combat applications of UGVs. It was established in FY 1990 at the Army Missile Command, with the Marine Corps providing the project manager. Its main responsibility is the detailed planning, management, and execution of the TUGV acquisition program.
- Explosive Ordnance Disposal Projects--The Joint Service EOD Office manages the programs for the teleoperated RECORM, already in EMD, and RONS.
- Rapid Runway Repair--The development of the RRR--an Air Force unique UGV--is carried out by the Air Force Civil Engineering Support Agency, located at Tyndall Air Force Base, FL.

- Physical Security Projects--OSD will rely on the DoD PSEMO at Ft. Belvoir, VA, for day-to-day management of UGV projects that require PSS&E expertise.

2. UGV Technology Enhancement and Exploitation Program

Currently the UGVTEE has two parts: DEMO I and DEMO II. The day-to-day management of DEMO I and DEMO II are the responsibility of the Army Research Laboratory (ARL) and DARPA, respectively. ARL will continue to serve as the focal point for near-term UGV-related technologies and will assist DARPA in the management of DEMO II. Communications and Electronics Command (CECOM) and TACOM serve as the focal points for communication and automotive technologies, respectively.

To accelerate the progress and maturation of autonomous navigation technology for ground vehicles that must operate in a battlefield environment and to establish an industrial R&D base for this technology, DARPA and OUSD(A)/TS signed an MOA in FY 1991 for the conduct of DEMO II. This MOA is reproduced in Appendix A of last year's UGVMP.

3. Interdepartmental and International Cooperation

There are a number of opportunities for cooperation on robotics and UGV activity between DoD and other departments. Some are being exploited--NIST and ORNL have contributed to the UGV program. Others, such as DoD/DoE cooperation on environmental restoration, are being seriously explored. Other important opportunities, such as DoD/ Department of Transportation cooperation on robotic ground transport, are likely to emerge soon. Every effort is being made to explore opportunities for cooperative R&D and to ensure that DoD takes advantage of work in other government departments.

Similarly, there is strong interest in UGV technology in a number of other countries, including Germany, United Kingdom, France, Japan, Canada, and Israel. Through exchange of visits and informal information exchanges, the groundwork is being established for possible future cooperative programs.